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(71) Applicant (*for all designated States except US*): SURFECT TECHNOLOGIES, INC. [US/US]; 12000 Candelaria, N.E., Albuquerque, NM 87112 (US).

(72) Inventors; and

(75) Inventors/Applicants (*for US only*): GRIEGO, Thomas, P. [US/US]; 1258 West Meadowlark Lane, Corrales, NM 87048 (US). SANCHEZ, Fernando, M. [US/US]; 10404 Gloria Place, N.E., Albuquerque, NM 87112 (US).

(74) Agent: SLUSHER, Stephen, A.; Peacock, Myers & Adams, P.C., Post Office Box 26927, Albuquerque, NM 87125-6927 (US).

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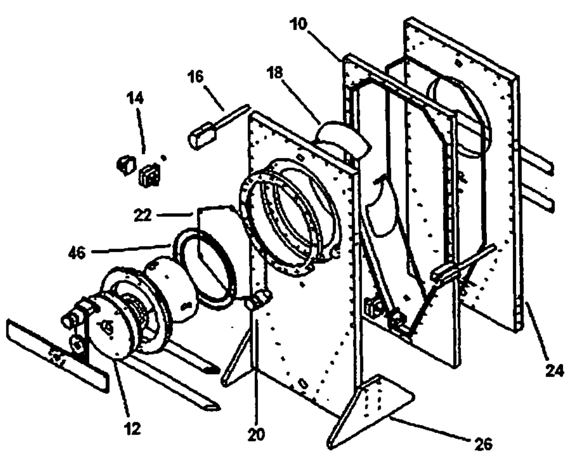
(54) Title: APPARATUS AND METHOD FOR HIGHLY CONTROLLED ELECTRODEPOSITION



(57) Abstract: An apparatus and method for highly controlled electrodeposition, particularly useful for electroplating submicron structures. Enhanced control of the process provides for a more uniform deposit thickness over the entire substrate, and permits reliable plating of submicron features. The apparatus includes a pressurized electrochemical cell (10) to improve plating efficiency and reduce defects, vertical laminar flow of the electrolyte solution to remove surface gases from the vertically arranged substrate, a rotating wafer chuck (12) to eliminate edge plating effects, and a variable aperture (18) to control the current distribution and ensure deposit uniformity across the entire substrate. Also a dynamic profile anode whose shape can be varied to optimize the current distribution to the substrate. The anode is advantageously able to use metallic ion sources and may be placed close to the cathode thus minimizing contamination of the substrate.

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APPARATUS AND METHOD FOR HIGHLY CONTROLLED ELECTRODEPOSITION

BACKGROUND OF THE INVENTION

Field of the Invention (Technical Field):

The present invention relates to an apparatus and method for electroplating substrates or other objects, particularly semiconductor wafers. The present invention can also be used to plate ceramic panels used in thin or thick film type packaging, as well as anti-reflective coatings of lenses and other types of glass substrates. The apparatus may also be used for microvia deposition, wafer bumping, and flip chip bumping.. The apparatus provides for a much higher control of the deposition parameters, enabling fine submicron features to be plated. The invention also relates to an anode for electrochemical processes whose profile can be varied to any desired shape. The anode may be used with metallic ion sources without contaminating the substrate.

Background Art:

Note that the following discussion is given for more complete background of the scientific principles and is not to be construed as an admission that such concepts are prior art for patentability determination purposes.

A traditional electroplating cell comprises a tank to hold the chemical solution, one or two anodes that are either of a soluble composition of the metal to be deposited or insoluble platinumized anodes. The item to be plated is mounted horizontally on the cathode, at a gap of approximately four inches from the anode(s). A DC power supply, operating with either a constant, switched or pulsed output, with an optional periodic polarity reverse is most often utilized in current cells. Configurations of this type do not provide sufficient control over the deposition process to enable the uniform plating of submicron features on a substrate. Nor can the operating geometries and other parameters of the cell be easily varied to accommodate different types of plating substrates or patterns, or to adjust the plating conditions to ensure uniformity and quality of the deposit.

It is known in the art to enhance the deposit uniformity by introducing an aperture to selectively mask off the edges of the substrate. However, when plating submicron structures it is critical that the size of the aperture be adjustable to more precisely control the thickness uniformity, whether before or during processing. In addition, an adjustable aperture enables the cell to be used

The aperture is preferably electrically insulating, and preferably comprises a circular opening which is variable in size, optionally during operation of the cell. The aperture preferably comprises an iris with at least three paddles. The opening is preferably continuously variable from a size larger than the size of the substrate to completely closed.

The anode is preferably situated less than approximately 5 cm, more preferably less than approximately 1 cm, and most preferably less than approximately 0.5 cm from the cathode. The metal ion source is preferably situated behind the anode, thereby minimizing contamination from reaching the substrate while the anode retains a constant surface profile. The surface profile of said anode is preferably controllably variable, and may be varied during operation of the cell. The anode preferably comprises parallel hollow electrically conducting tubes.

The apparatus may optionally comprise a magnet, such as an electromagnet or at least one permanent magnet. The magnet preferably provides for the codeposition of magnetic particles along with the electrochemical deposition on the substrate. The codeposition may occur before, during, and/or after the electrochemical deposition. The strength of the magnet is preferably adjusted to provide a desired concentration of magnetic particles on the substrate.

The invention is further of an apparatus for performing multiple electrochemical depositions on a substrate, the apparatus comprising an anode having a variable surface profile, a cathode with a vertical mounting surface, a pressurized cell to contain electrolytic solution, a closed, optionally filtered system for circulation of the solution, and an aperture with a variably sized opening disposed between the anode and the cathode; wherein a vertical flow of the electrolytic solution is substantially laminar in the vicinity of the cathode. The multiple depositions are preferably carried out without opening the cell between each deposition, even though the surface profile of the anode and/or the size of the opening are preferably controllably varied as desired for each deposition.

The invention is also of a method of electrolytically depositing a material on a substrate, the method comprising the steps of providing an electrolytic cell, providing an anode, mounting the substrate on a cathode so that a surface of the substrate is vertically disposed, disposing an aperture between the anode and cathode, providing laminar flow of electrolyte solution through a cell, pressurizing the solution to a desired pressure, and providing an electric potential difference between the cathode and the anode. The solution is preferably filtered. Optionally, submicron features on the substrate are uniformly plated.
The substrate is preferably rotated about a horizontal axis perpendicular to the surface, and the

invention will be set forth in part in the detailed description to follow, taken in conjunction with the accompanying drawings, and in part will become apparent to those skilled in the art upon examination of the following, or may be learned by practice of the invention. The objects and advantages of the invention may be realized and attained by means of the instrumentalities and combinations particularly pointed out in the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are incorporated into and form a part of the specification, illustrate several embodiments of the present invention and, together with the description, serve to explain the principles of the invention. The drawings are only for the purpose of illustrating a preferred embodiment of the invention and are not to be construed as limiting the invention. In the drawings:

Figure 1 is an exploded view of a preferred embodiment of the electrodeposition apparatus of the invention;

Figure 2 is an isometric view of the cell and reservoir;

Figure 3 shows a cross section of the cell;

Figure 4 depicts a close up of the cross section of the plating area of the cell;

Figure 5 shows the chuck in position for wafer loading or unloading;

Figure 6 shows the wafer in the loaded position;

Figure 7 shows the chuck rotated to the vertical position;

Figure 8 shows a cross section of the wafer chuck;

Figure 9 is a detail of the rotating wafer mount;

Figure 10 is an isometric view of the rear of the chuck, showing the rotation mechanism;

Figure 11 is a cutaway view of the cell depicting the iris fully open;

Figure 12 is a cutaway view of the cell depicting the iris partially masking the substrate;

Figure 13 is a cutaway view of the cell depicting the iris fully closed;

Figure 14 shows an isometric view of one embodiment the dynamic profile anode assembly;

Figure 15 shows an exploded view of the dynamic profile anode assembly;

Figure 16 shows a top view and cross section of the dynamic profile anode assembly depicting a convex surface profile;

Figure 17 depicts the dynamic profile anode and clamp showing a convex surface profile;

Figure 18 is an exploded view of Figure 17;

Figure 19 is a cross sectional view of a second embodiment of the dynamic profile anode with a flat surface profile;

may be integral with the cell itself. The electrolyte solution is pumped into cell **10** through solution inlet **36**. Pressure valve **38** regulates the pressure in the cell, as more fully described below, and controls the circulation of the electrolyte solution back to reservoir **30**.

Unlike traditional electroplating devices, the entire circulation path of the solution, and the process environment in which the wafer is placed, is preferably enclosed, and more preferably comprises at least one filter, including but not limited to a submicron filter. Thus the electroplating environment is equivalent to a clean room, without requiring the latter's expense, and ensures a reliable and uncontaminated deposit process.

As shown in Figure 3, connected to the cell's cathode will preferably be the negative terminal **40** of a DC power supply, operating with either a constant, switched or pulsed output, or with optional periodic polarity reversal, and connected to anode **100** will preferably be the positive terminal **42** of the power supply. Figure 4 is an enlarged detail.

Chuck **12** is preferably comprised of articulating door **44** that can be opened and can interface with automation known in the art for mounting and dismounting of the substrate, permitting automated substrate loading and unloading. As shown in Figures 5 and 6, substrate **50** is mounted on chuck **12**, which is preferably in the horizontal position. Chuck **12** holds substrate **50** on a flat surface and supplies the cathodic current to the surface of substrate **50** via at least one contact **52**. Thus chuck **12**, and more specifically substrate **50**, acts as the cathode in the present system, and the terms are used interchangeably herein. Cell **10** of the present invention is capable of handling substrates in a large size range, such as wafers used in the semiconductor industry, including but not limited to those from 75 mm to 300 mm in diameter. Optionally, the edges of the substrate may be masked by a grip ring, preferably comprised of both metallic and insulating materials, that will supply current at the edge of the substrate while masking the edge of the current contact itself so that unnecessary deposits don't occur on the contact. Figure 7 shows door **44** rotated into the vertical position about pivot assembly **14** so it is ready to slide along guide rods **16** and seal the opening in bulkhead door **26**.

Chuck **12** is preferably rotatable, which provides advantages in uniformity of deposit that are described more fully below. Various views of the rotation mechanism are presented in Figs. 8-10. Motor **58**, optionally mounted on motor mount **66**, is preferably used to provide such rotation, connecting via gear **64** or other rotation transfer means, such as a belt, to rotating shaft **62** that protrudes through o-ring seals **60** in articulating door **44**. A DC current is preferably fed through shaft **62** via negative terminal **40**, which will continuously supply cathodic current during the process run.

deposit, such as a metallic interconnect, to the substrate or wafer is critical to assure the high reliability necessary for electronic components.

For applications in the submicron range, particulates, pores, and micropittings that would normally be acceptable in traditional plating applications are not tolerable because of the small size of the features to be plated as well as the required thinness of the deposit. Thus the overall control of micropittings is of paramount importance if semiconductor wafers are to be electroplated. By using pressurization to minimize gas formation, the integrity of the initial deposit on the surface of the wafer (when the voltage or the potential is at its highest), which creates the first boundary layer between the substrate and the metal being deposited, will be greatly improved. This results in a surface morphology of sufficient quality to successfully plate submicron structures.

The vertical configuration of the preferred embodiment of cell **10** also helps to reduce the presence of undesirable gas and gas bubbles at the surface of substrate **50** due to the laminar flow of electrolyte past the surface, which acts together with gravity to remove the gas upward away from the interface area of the substrate. The electrolyte optionally passes through baffles which distribute the pressure within the solution and help create laminar flow. Laminar flow formation is also preferably promoted by utilizing a non-rectangular shape of cell **10** adjacent to solution inlet **36**, preferably a triangular or conical shape, as shown in Figure 1. The length of cell **10** is long enough to transform the turbulent flow of the plating solution when introduced in the base of the cell to a laminar flow as it passes the surface of the wafer. The pressurization of the cell contributes to shortening the overall length of the cell required to achieve the laminar flow.

Laminar flow also enhances the plating solution by continuously and uniformly supplying solution of the optimum temperature and pH and ion species to the substrate. By sweeping out gases and supplying a continuous, reliable supply of electrolyte to the substrate, a more robust and uniform deposit is achieved, allowing for a greater range of chemical compositions for high-throw or low-throw baths to be utilized, giving the chemical process engineer more latitude. If laminar flow is not present, a defect or non-uniformity of the deposit's thickness or mechanical properties may result.

The present invention also comprises further multiple means to greatly enhance the uniformity of the thickness of the deposit on substrate **50**. The thickness can be kinetically controlled across the entire substrate by rotation of substrate **50** as described above, and by selective masking of the substrate's exposure to anode **100**, which techniques serve to provide a far more uniform current density at all points on substrate **50**.

uniformly plated regardless of the line width, pitch, or density of the pattern.

Also, different wafer designs require different optimal settings of the aperture size due to differences in the total metallization area and distribution and density of features to be plated. The variable size aperture allows the user to precisely optimize the system for each wafer design. And an adjustable aperture means that the user does not have to replace the aperture for each separate wafer design.

The present invention is also of a dynamic profile anode **100** that may be used for plating, electroplating, electrodeposition, chemical and mechanical polishing (CMP), electropolishing, etching, electrolysis, or any other electrochemical process. Although shaped anodes are known in the art, the present invention is of an anode whose profile can be modified before or even during processing. Examples of profiles include but are not limited to flat, convex, domed, curved, hemispherical, conical, pyramidal, or any combination thereof. The shape used will be determined through experimentation and optimized for various types of wafer patterns. For example, conical-type shapes concentrate the ionic current toward the center of the substrate or cathode, thereby providing an additional method of maximizing the uniformity of the deposit thickness across the substrate.

Figure 14 shows one embodiment of the anode assembly, with an exploded view in Figure 15 and a cross section in Figure 16. The assembly comprises anode **100**, which is seated in anode diaphragm **110**. Filter **120**, preferably cloth or polypropylene, allows ions to pass but prevents contamination from soluble metallic plating media in basket **130** from reaching anode **100** and eventually the cathode. Basket **130**, which preferably comprises titanium or another non-soluble metal, is connected via contact rods **140** to base **150**.

Figures 17 and 18 detail the construction of anode **100**. Anode **100** is comprised of tubes **102** which form a stack up which provides the shape of the surface profile of anode **100**, and clamp ring **104** which secures tubes **102** in place so it is dimensionally stable once the desired surface profile is achieved. Contact bus plates **160** conduct electrical current to anode **100**.

Another embodiment of dynamic profile anode **100** is shown in Figures 19-22. Figure 19 is a cross section view showing a flat surface profile. Current is provided from positive terminal **42** through o-ring seals **170** to basket **130**, clamp ring **104** and tubes **102**. Figure 20 depicts a convex surface profile, while Figures 21 and 22 show a cross section view and isometric view, respectively, of anode **100** with a conical surface profile. The surface profile may be changed by removing clamp ring

rapidly drained, and a rinsing chemistry is preferably circulated throughout the cell. The rinsing step may be repeated for a number of cycles to achieve a desired level of purity of the rinsed wafer surface. Subsequent chemical processes may then be performed to deposit additional electroplated films or multiple compositions. For example, a substrate may be plated with a nickel film over a copper film and followed by a tin film. Or ceramic panels used in thick film type packaging, which require multiple layer film formation, can be produced. Because the system is preferably closed and filtered, clean room conditions with little contamination can be maintained throughout the entire multiple operation process. This feature is also facilitated by the adjustable aperture and dynamic profile anode, which allows the user to choose the optimal iris size (or sizes) and anode profile for a particular process without having to open the cell and replace the aperture.

Optionally the chuck may be magnetic, which allows for magnetic particle codeposition. This process is more fully described in U.S. Provisional Patent Application Serial No. 60/519,813, entitled "Particle Coelectrodeposition", and U.S. Patent Application Serial No. 10/728,636, entitled "Coated and Magnetic Particles and Applications Thereof". One example of such a chuck is the back seal electrolytic vacuum chuck, disclosed in U.S. Provisional Patent Application Attorney Docket No. 31248-5, entitled "Pressurized Autocatalytic Vessel and Vacuum Chuck", filed on February 4, 2004. The specifications and claims of these references are incorporated herein by reference. One embodiment of such a chuck is shown in Figure 23, which is identical to Figure 8 except that it includes electromagnet **70**. The magnetic field may be provided by an electromagnet as depicted, or alternatively a permanent magnet, an array of magnets, or the like. The presence of the magnetic field allows magnetic particles to be codeposited on substrate **50** in a highly controlled manner before, during, or after the deposition of the electrolytic plating, providing numerous chemical, material, and mechanical advantages to the deposited structures.

Figure 24 depicts a schematic and flow diagram of a preferred embodiment of a co-deposition tool and process. Pump **290** pumps electrolyte stored in tank **264** to mixer **320**, where it is mixed with a slurry of magnetic particles in suspension which was pumped from slurry tank **300** by slurry pump **310**. The suspension-electrolyte mixture enters cell **10** and proceeds upward in laminar flow to the codeposition area comprising anode **100** and substrate **50**. Substrate **50** preferably rotates via motor **58**. Electromagnet **70** attracts magnetic particles from the suspension-electrolyte so that they are codeposited on substrate **50** along with the electrochemical deposition. Controller **230** controls deposition parameters, such as the electrode voltage via DC power supply **200** and the concentration of magnetic particles in the suspension-electrolyte mixture via slurry pump **310**.

CLAIMS

What is claimed is:

1. An apparatus for electrochemical deposition on a substrate, said apparatus comprising:

an anode;

a cathode with a vertical mounting surface;

a pressurized cell to contain electrolytic solution; and

an aperture disposed between said anode and said cathode;

wherein a vertical flow of said electrolytic solution is substantially laminar in a vicinity of said cathode.

2. The apparatus of claim 1 further comprising a reservoir.

3. The apparatus of claim 2 wherein the reservoir and cell comprise a closed system.

4. The apparatus of claim 2 further comprising at least one filter.

5. The apparatus of claim 4 wherein at least one of said at least one filter is a submicron filter.

6. The apparatus of claim 1 wherein the substrate comprises a semiconductor wafer.

7. The apparatus of claim 6 wherein the wafer is coated so that only certain features on the wafer receive the deposition.

8. The apparatus of claim 7 wherein said features are submicron features.

9. The apparatus of claim 1 wherein the cell is pressurized to at least approximately one atmosphere above ambient pressure.

10. The apparatus of claim 9 wherein the cell is pressurized to at least approximately two atmospheres above ambient pressure.

11. The apparatus of claim 1 wherein said cathode rotates about a horizontal axis perpendicular to said mounting surface.

26. The apparatus of claim 25 wherein said anode is situated less than approximately 0.5 cm from said cathode.

27. The apparatus of claim 1 wherein a metal ion source is situated behind said anode, thereby minimizing contamination from reaching the substrate while said anode retains a constant surface profile.

28. The apparatus of claim 1 wherein a surface profile of said anode is controllably variable.

29. The apparatus of claim 28 wherein said surface profile can be varied during operation of said cell.

30. The apparatus of claim 28 wherein said anode comprises parallel hollow electrically conducting tubes.

31. The apparatus of claim 1 further comprising a magnet.

32. The apparatus of claim 31 wherein said magnet comprises an electromagnet.

33. The apparatus of claim 31 wherein said magnet comprises at least one permanent magnet.

34. The apparatus of claim 31 wherein said magnet provides for codeposition of magnetic particles with electrochemical deposition on the substrate.

35. The apparatus of claim 34 wherein a strength of said magnet is adjusted to provide a desired concentration of magnetic particles on the substrate.

36. An apparatus for performing multiple electrochemical depositions on a substrate, said apparatus comprising:

an anode having a variable surface profile;
a cathode with a vertical mounting surface;
a pressurized cell to contain electrolytic solution;
a closed system for circulation of the solution; and
an aperture with a variably sized opening disposed between said anode and said cathode;

opening of the aperture.

46. The method of claim 41 wherein the step of providing an anode comprises situating the anode less than approximately 5 cm from the cathode.

47. The method of claim 46 wherein the step of providing an anode comprises situating the anode less than approximately 1 cm from the cathode.

48. The method of claim 47 wherein the step of providing an anode comprises situating the anode less than approximately 0.5 cm from the cathode.

49. The method of claim 41 wherein the step of providing an anode comprises situating the anode between a metallic ion source and the cathode.

50. The method of claim 49 wherein the step of providing an anode comprises minimizing contamination from reaching the cathode while retaining a constant surface profile.

51. The method of claim 41 wherein the step of providing an anode comprises controllably varying a surface profile of the anode.

52. The method of claim 41 wherein the mounting step further comprises providing a magnetic field.

53. The method of claim 52 further comprising the step of using the magnetic field to codeposit magnetic particles with the material on the substrate.

54. The method of claim 53 further comprising varying the magnetic field to adjust the composition of the magnetic particles on the substrate.

55. A method of performing multiple electrolytic depositions on a substrate, the method comprising the steps of:

a. providing a pressurized electrolytic cell;

b. providing an aperture with a variably sized opening;

c. optimizing deposition parameters of the cell including a pressure of the cell and a size of the opening for a desired deposition;

68. The anode of claim 66 wherein the receptacle is on a side of the anode opposite the surface profile.

69. The anode of claim 68 wherein the anode minimizes contamination from reaching a cathode while retaining a constant surface profile.

70. The anode of claim 56 wherein the process is selected from the group consisting of plating, electroplating, electrodeposition, chemical and mechanical polishing (CMP), electropolishing, etching, and electrolysis.

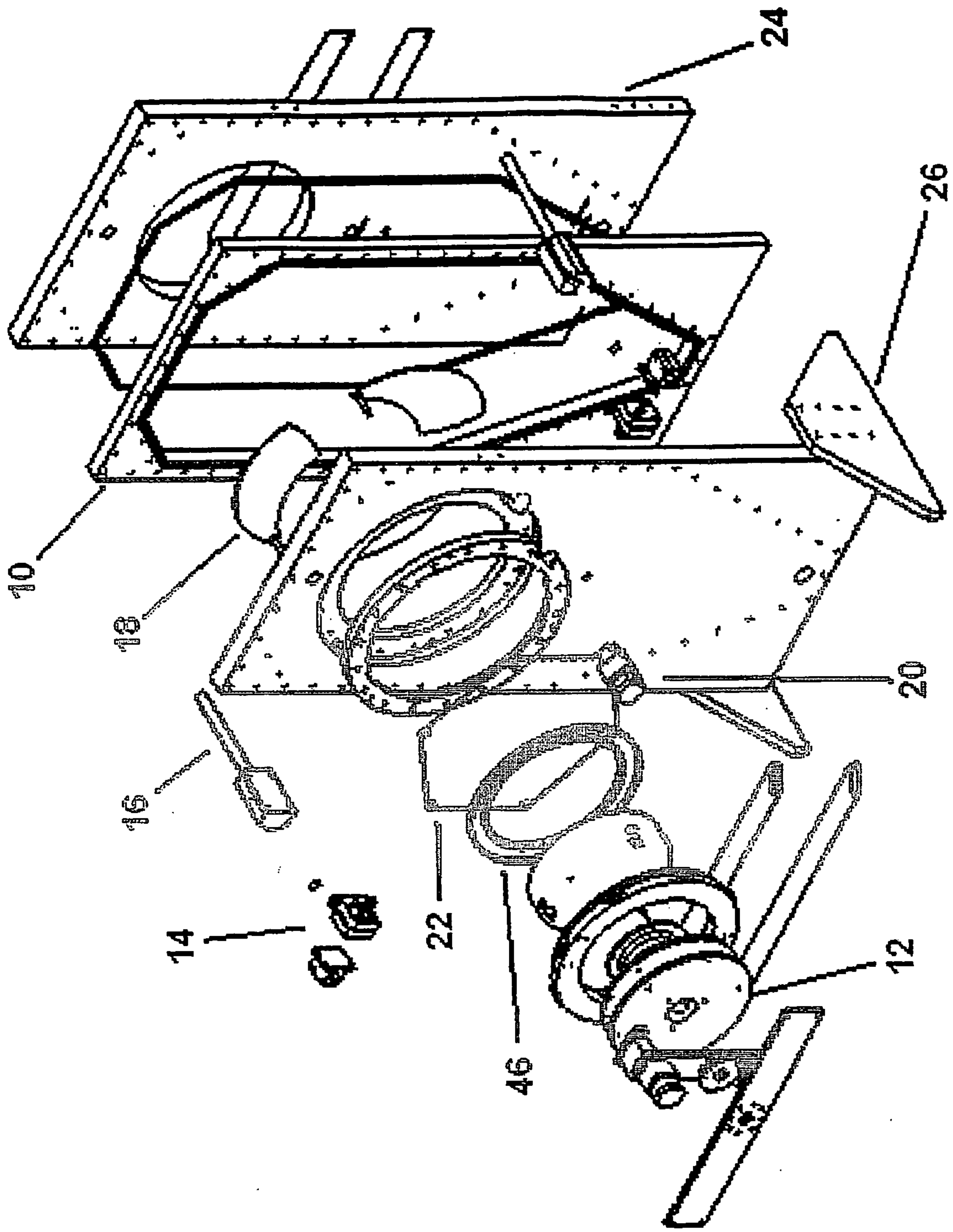

Figure 1

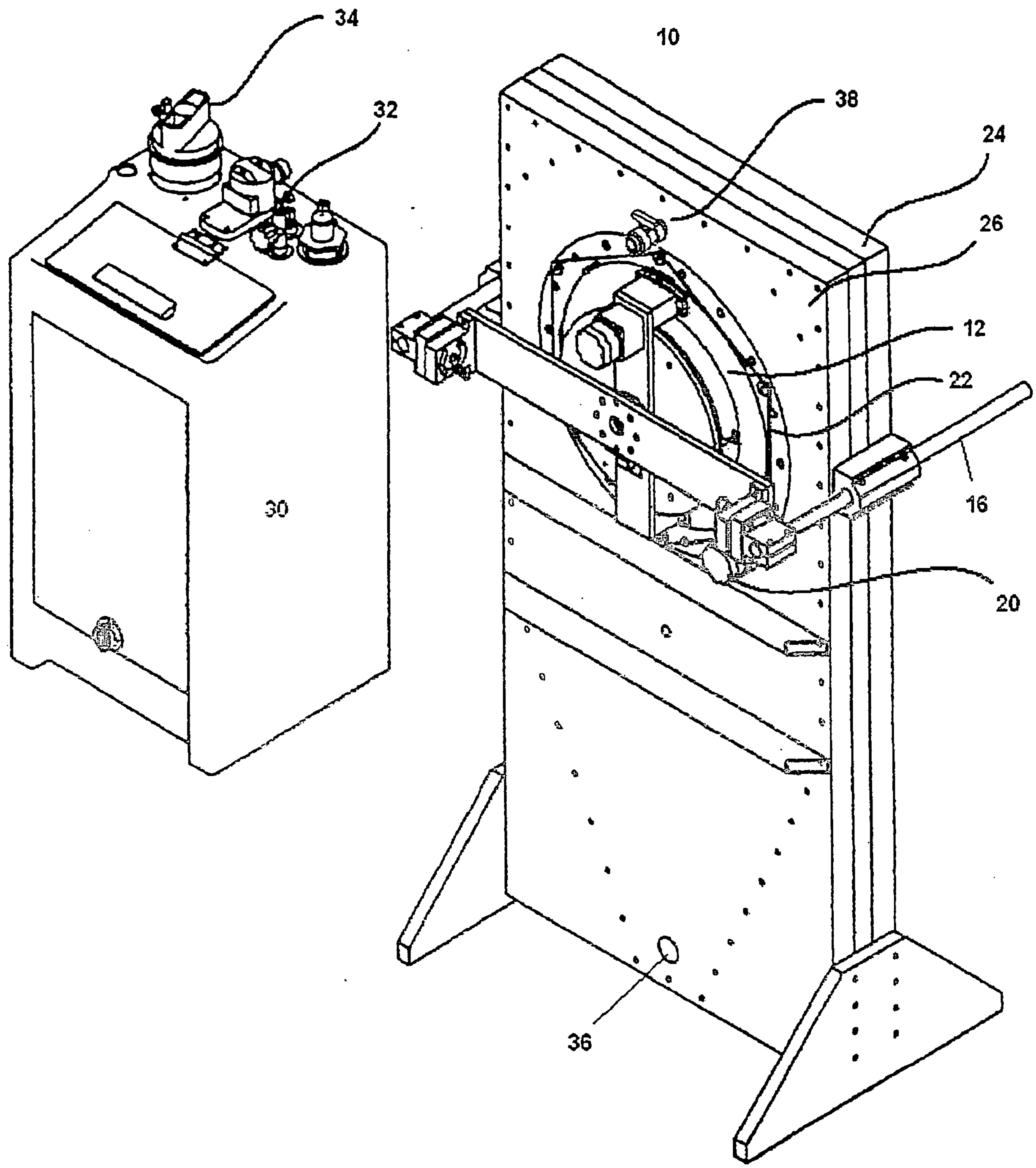

Figure 2

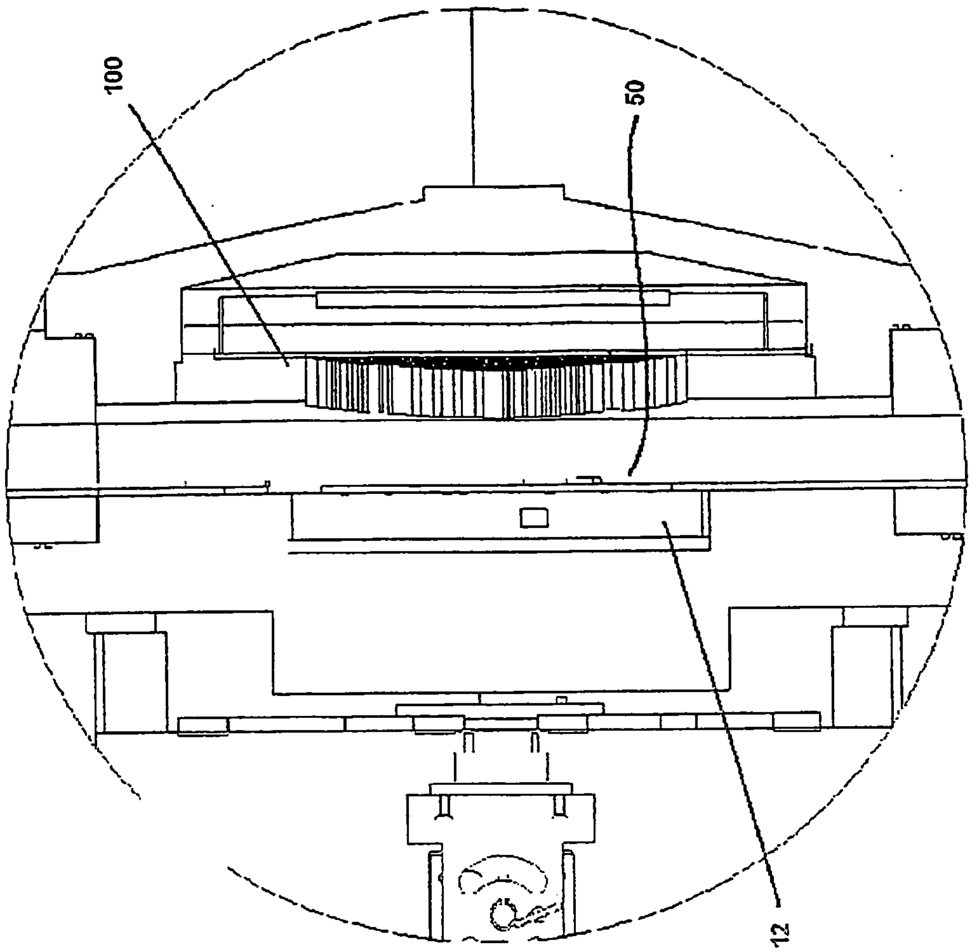

Figure 4

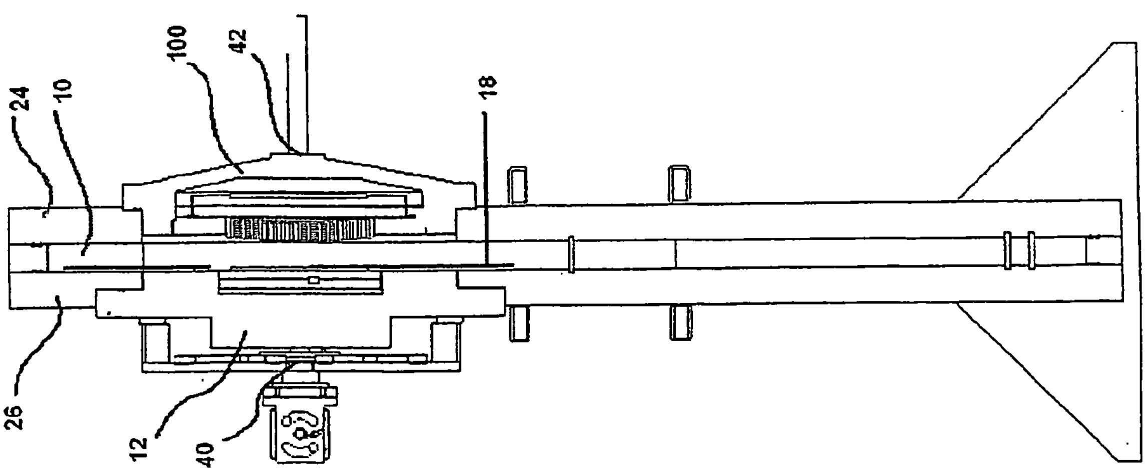

Figure 3

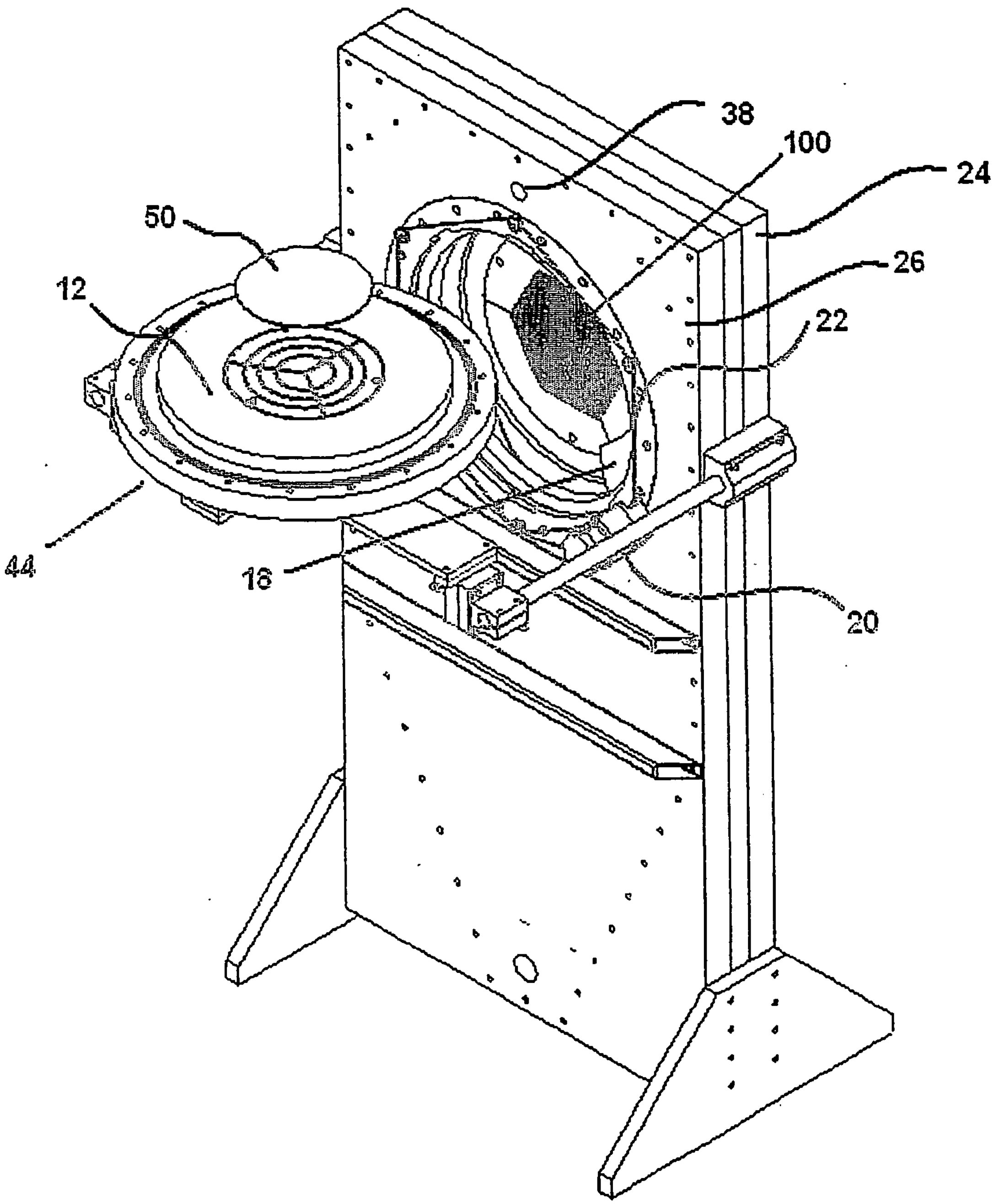

Figure 5

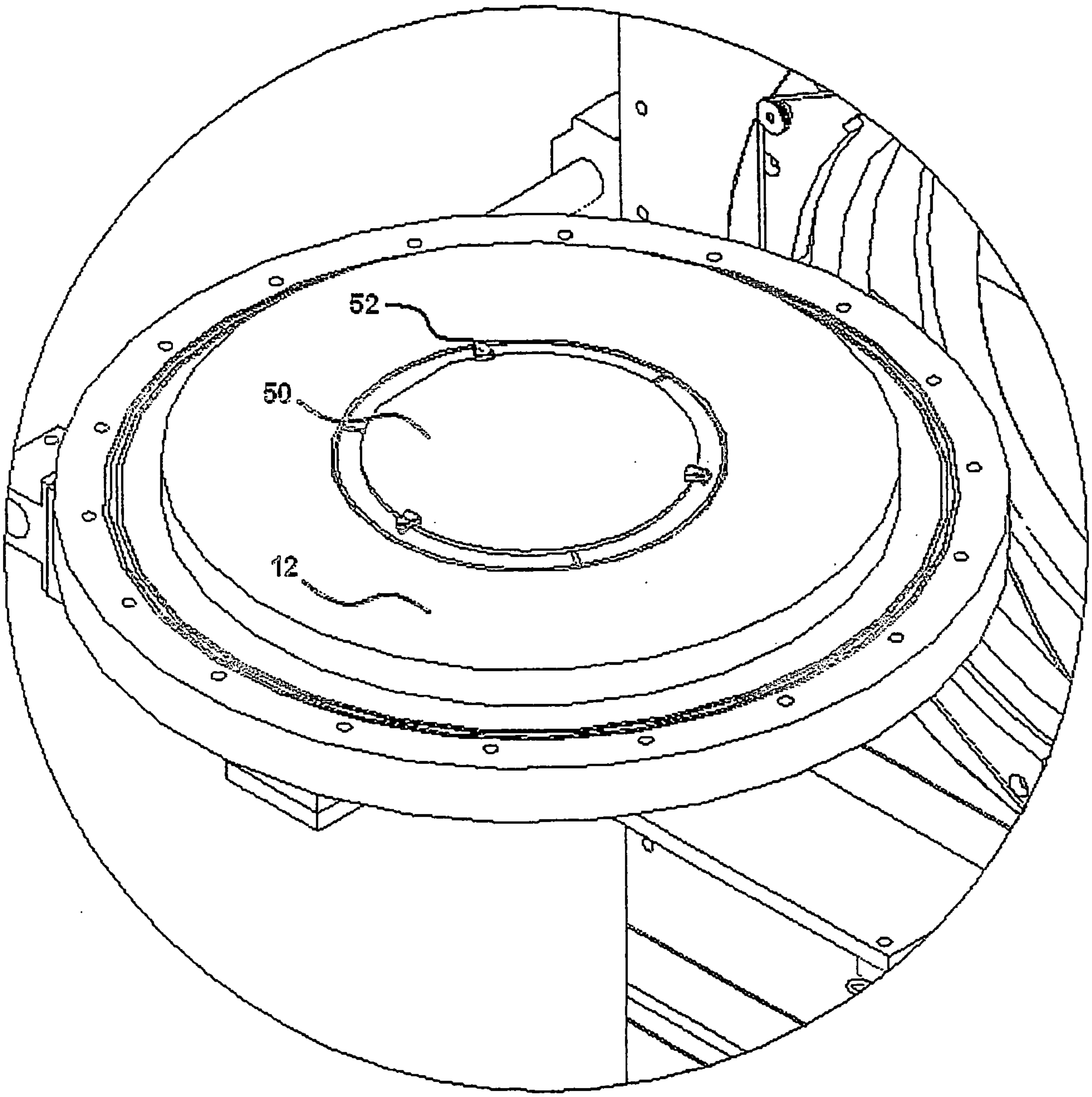

Figure 6

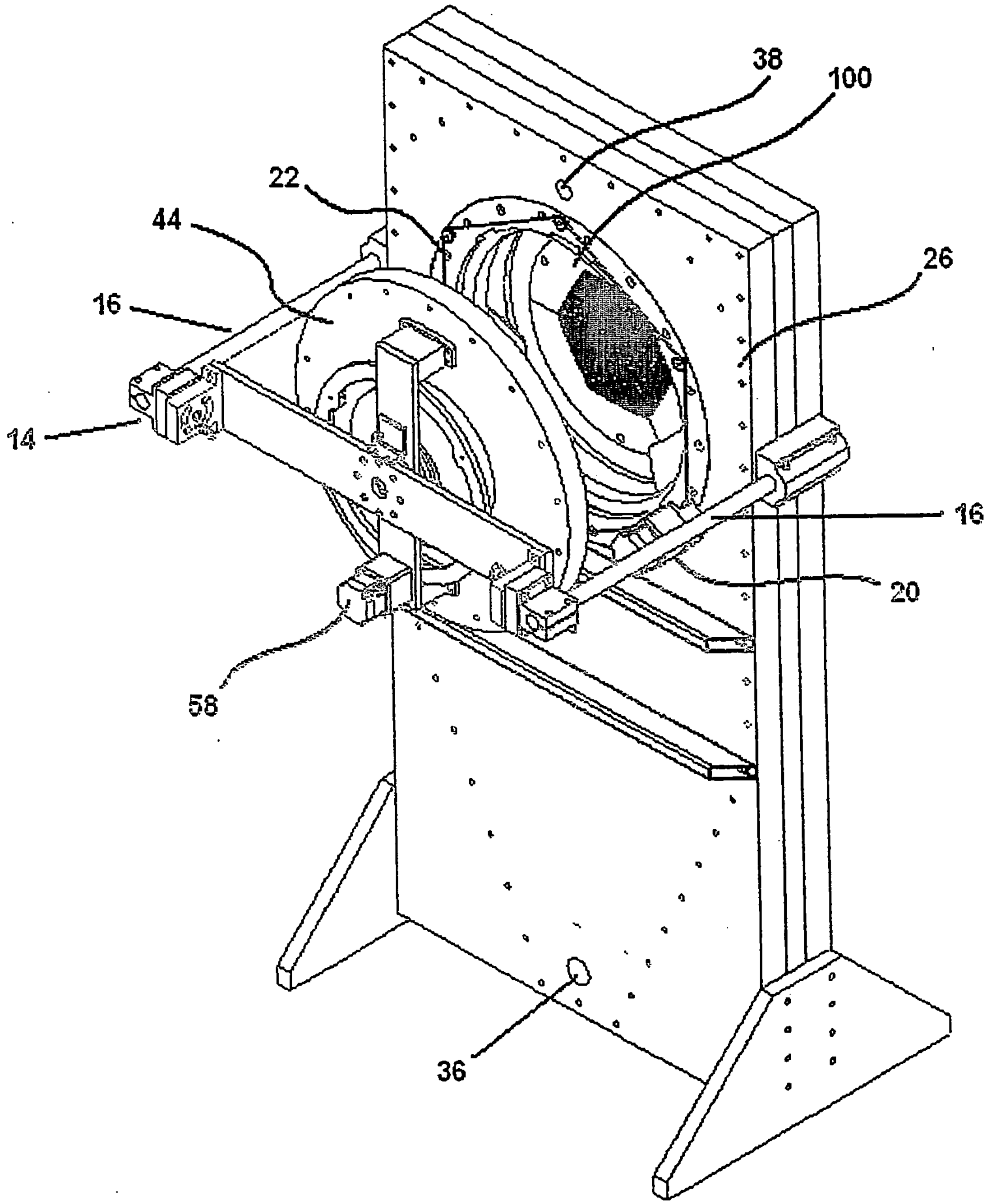

Figure 7

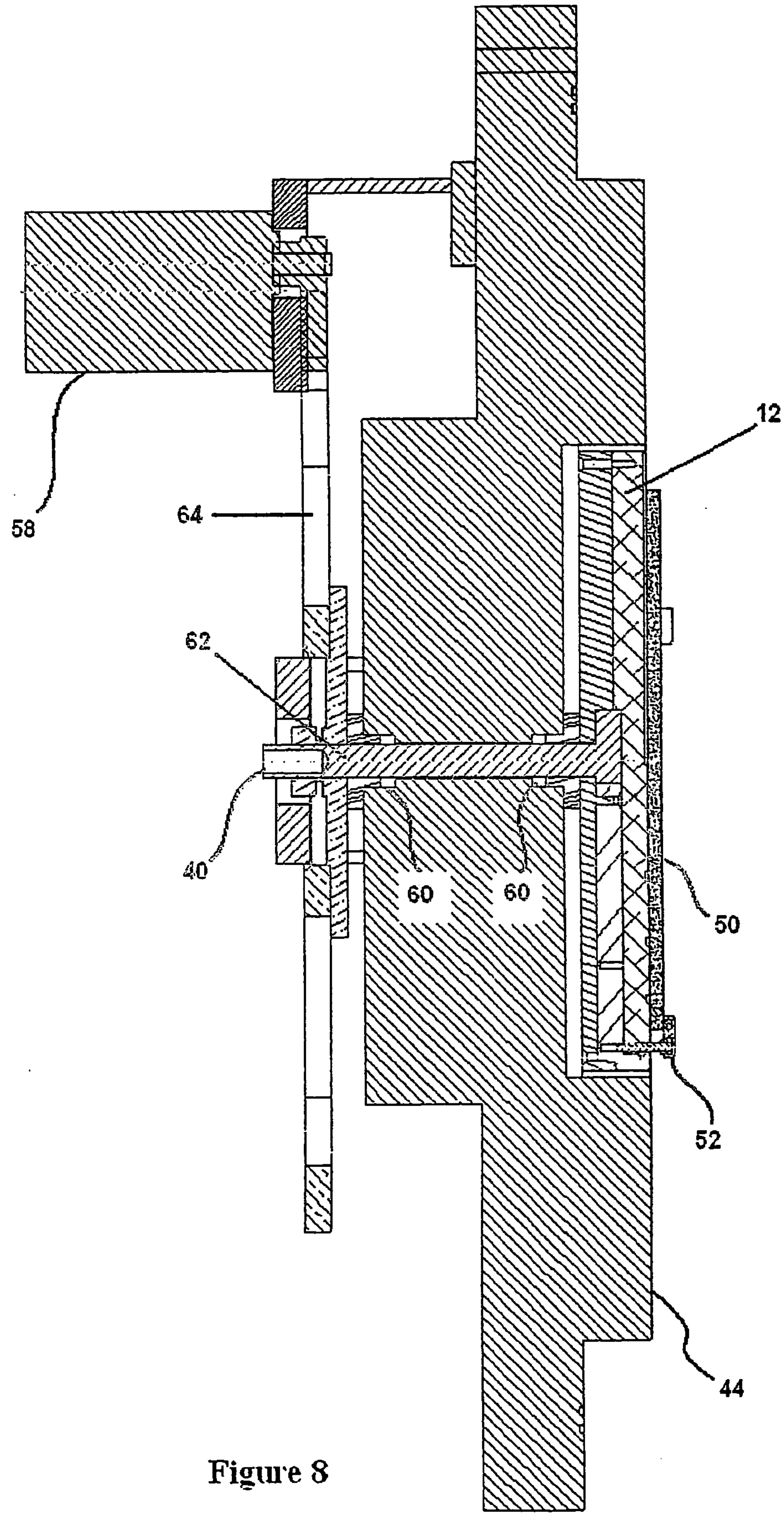

Figure 8

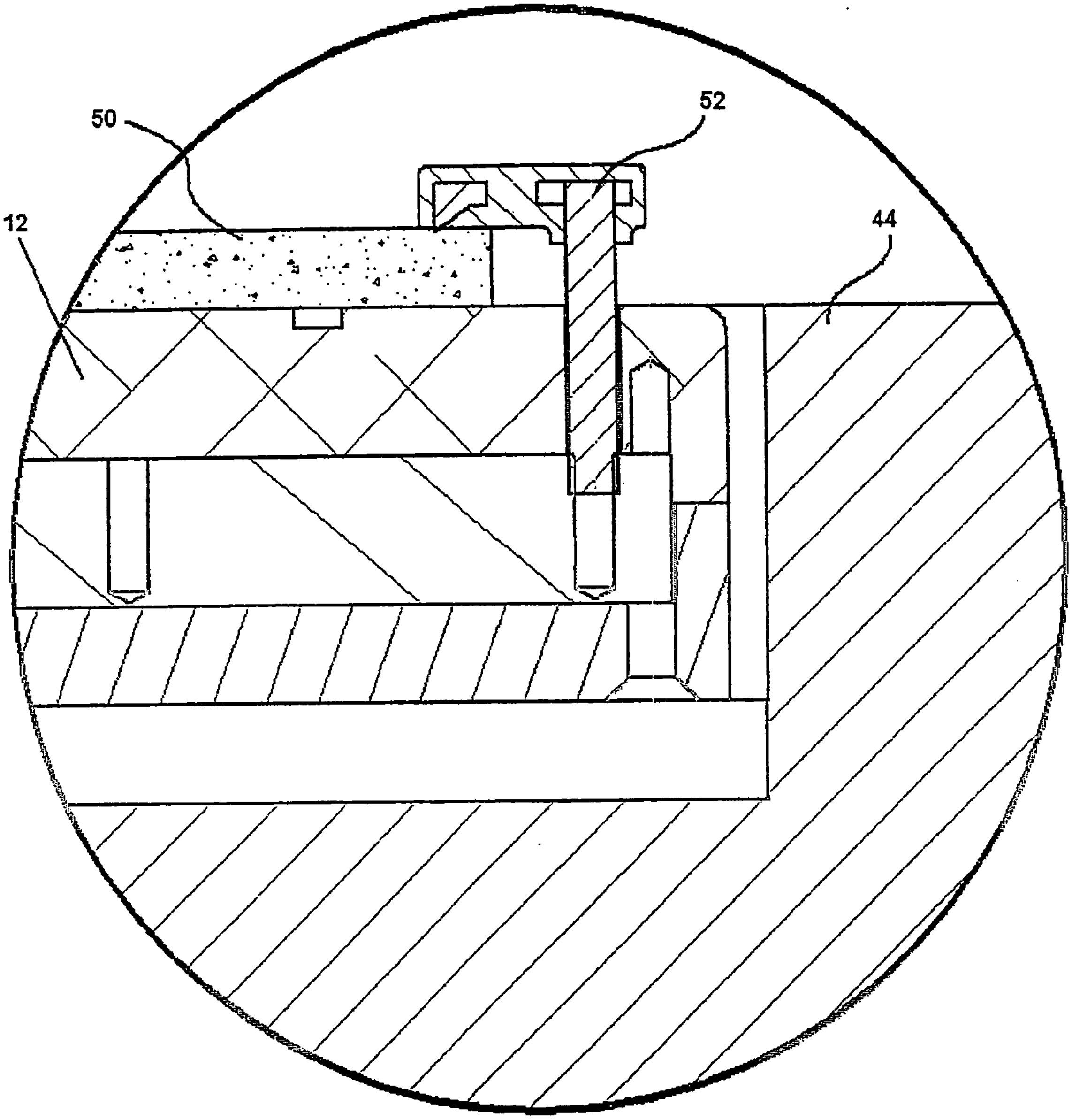

Figure 9

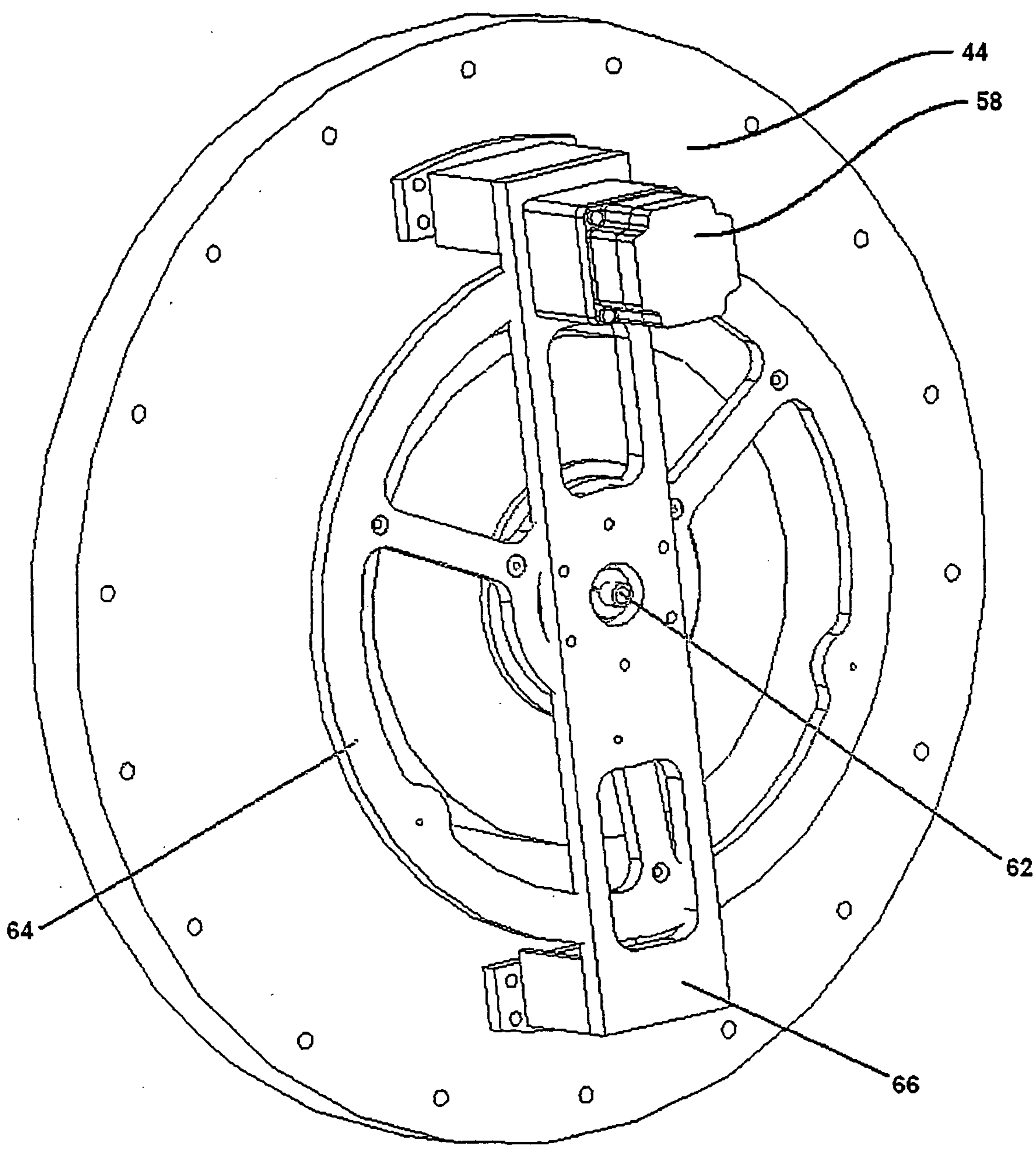

Figure 10

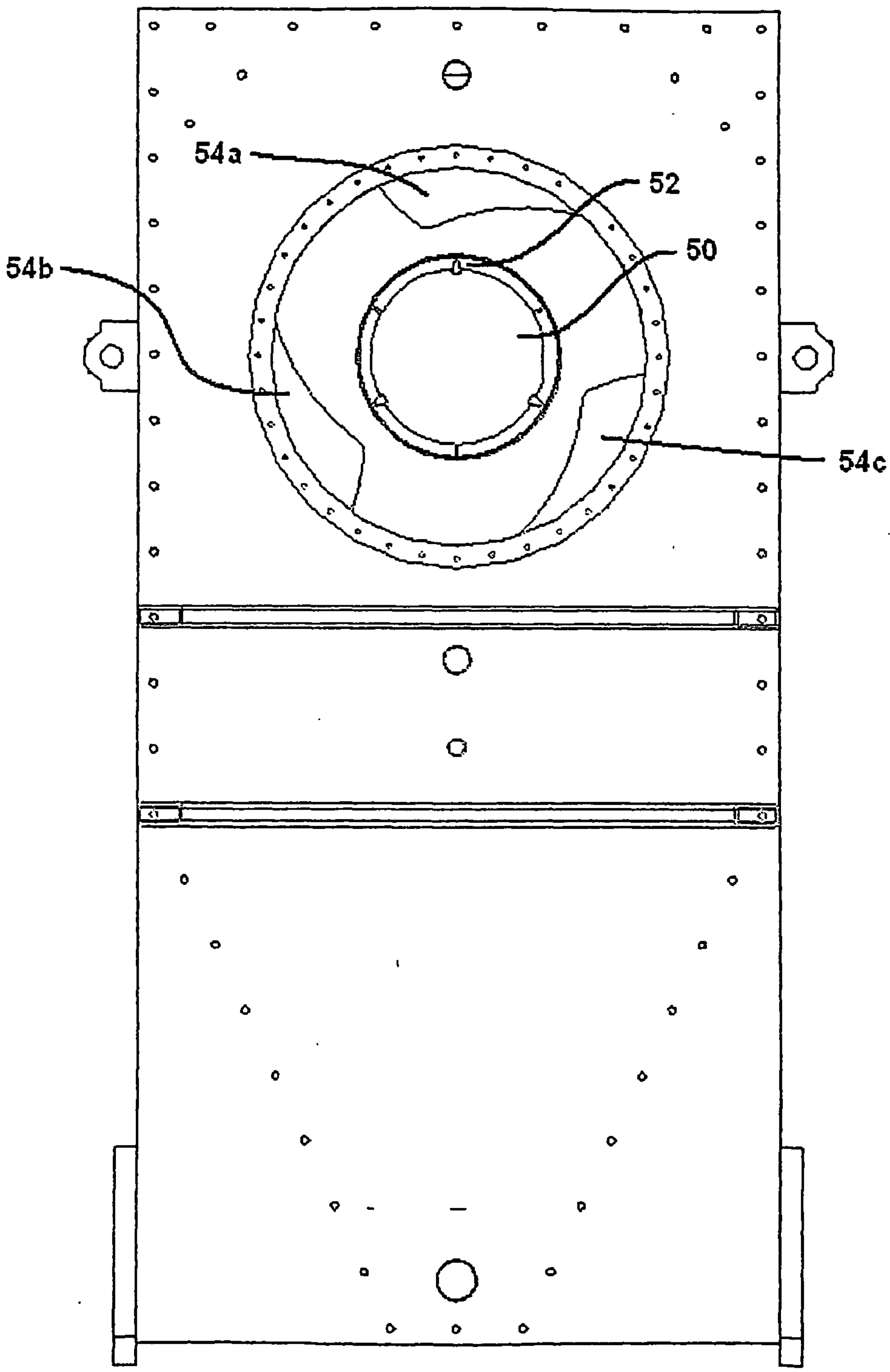

Figure 11

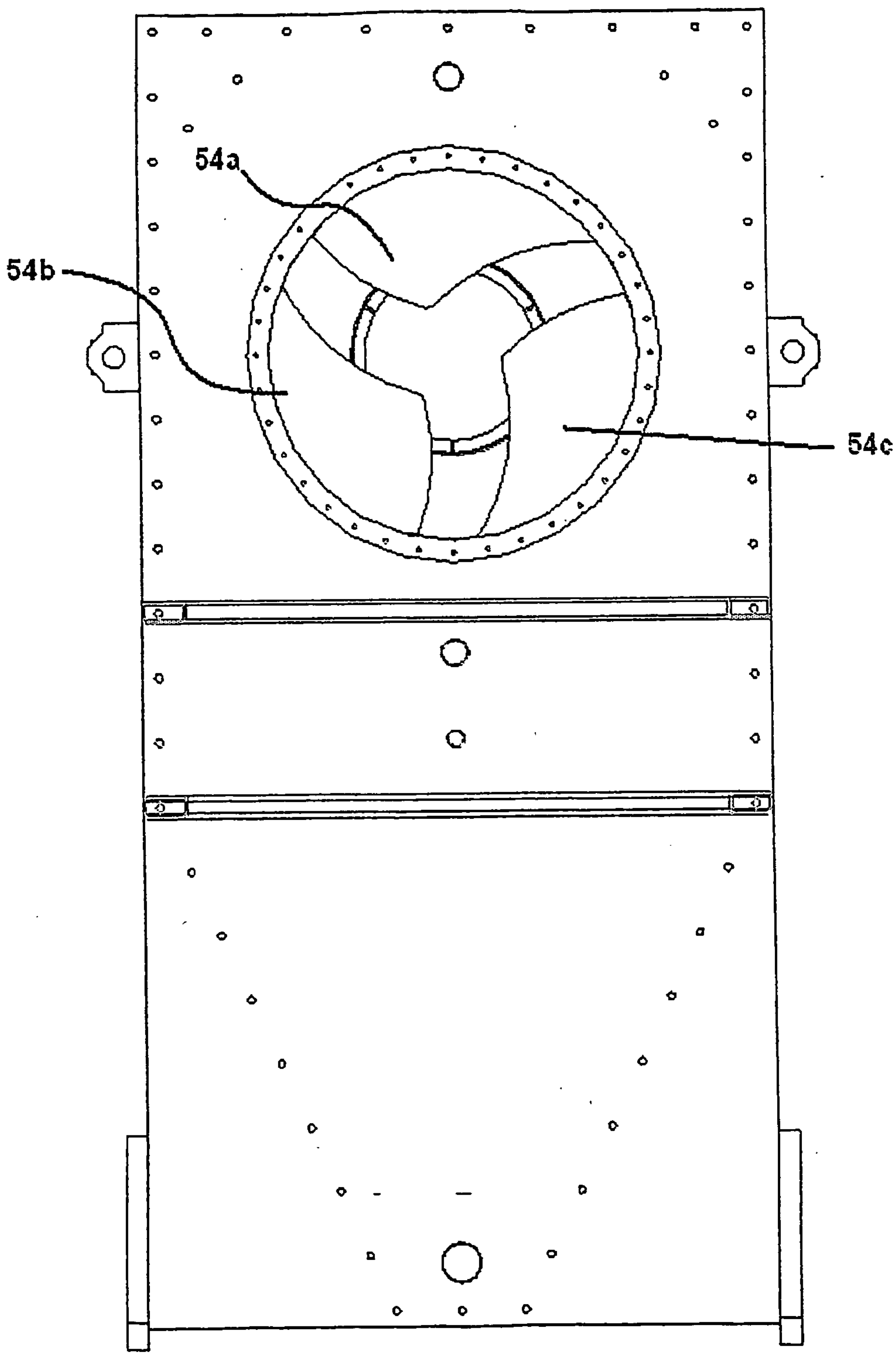

Figure 12

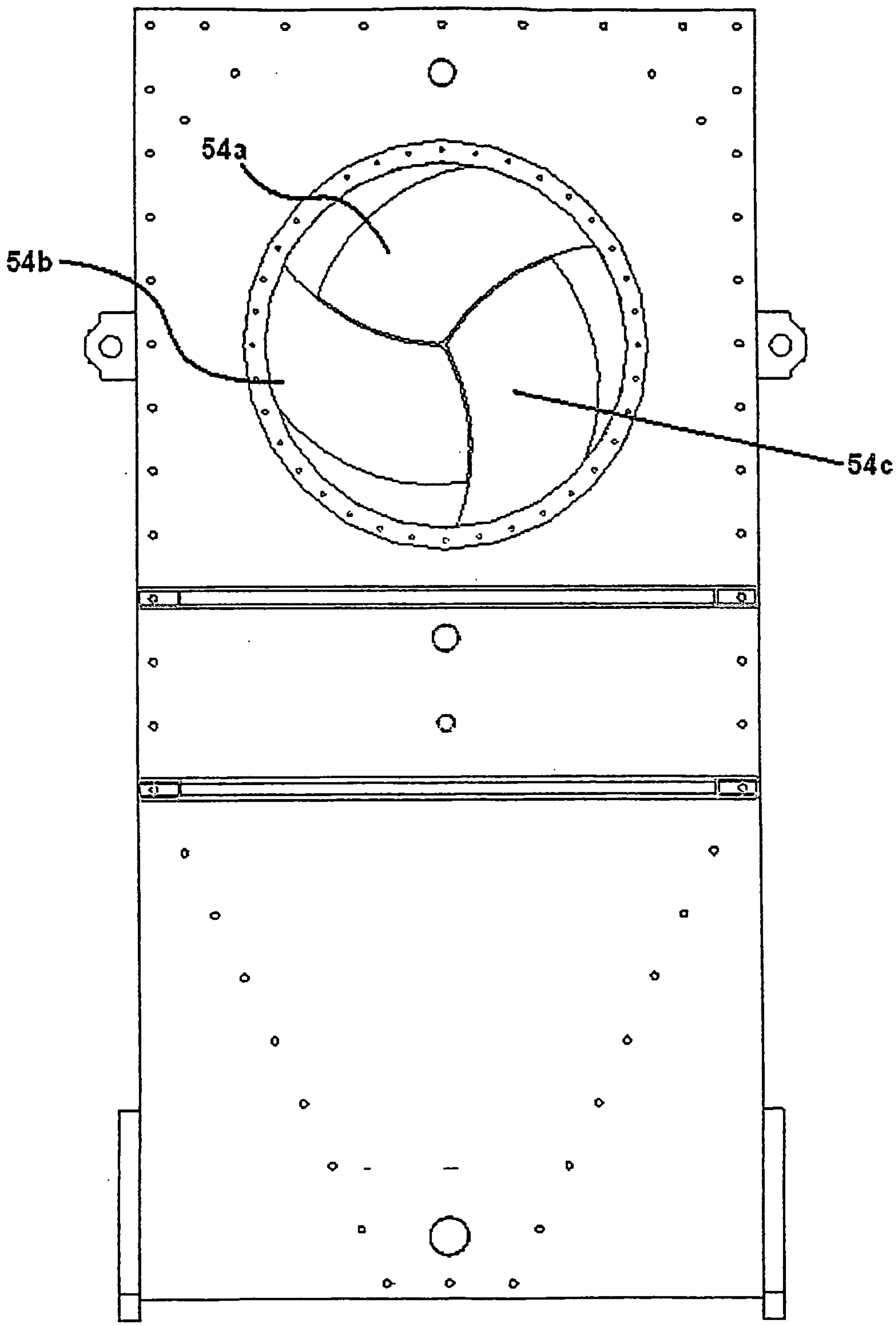

Figure 13

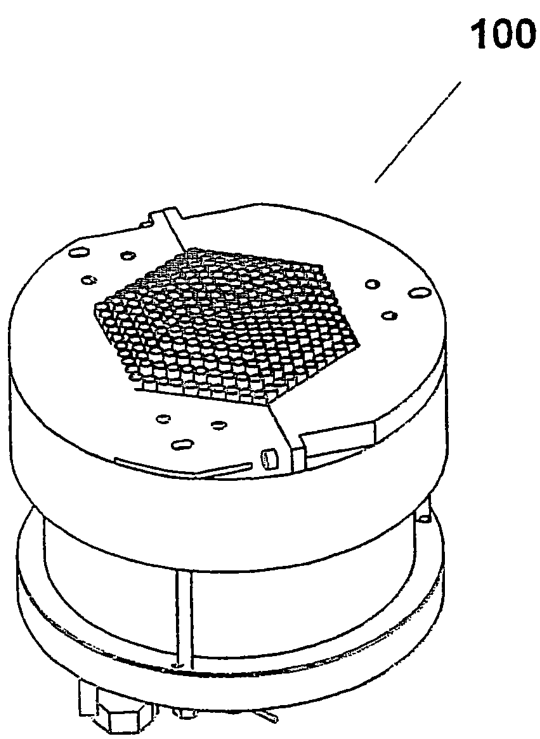

Figure 14

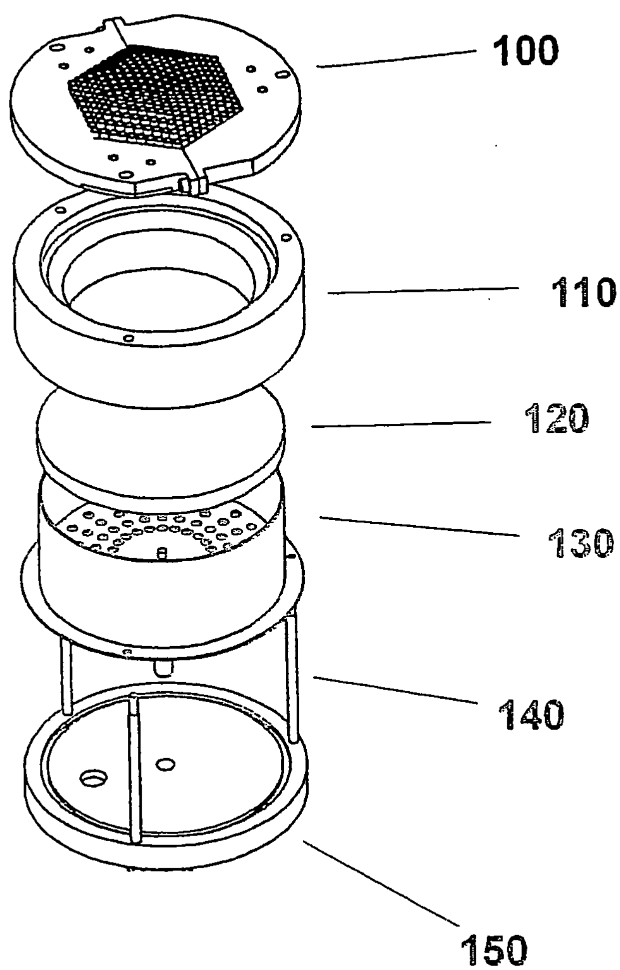

Figure 15

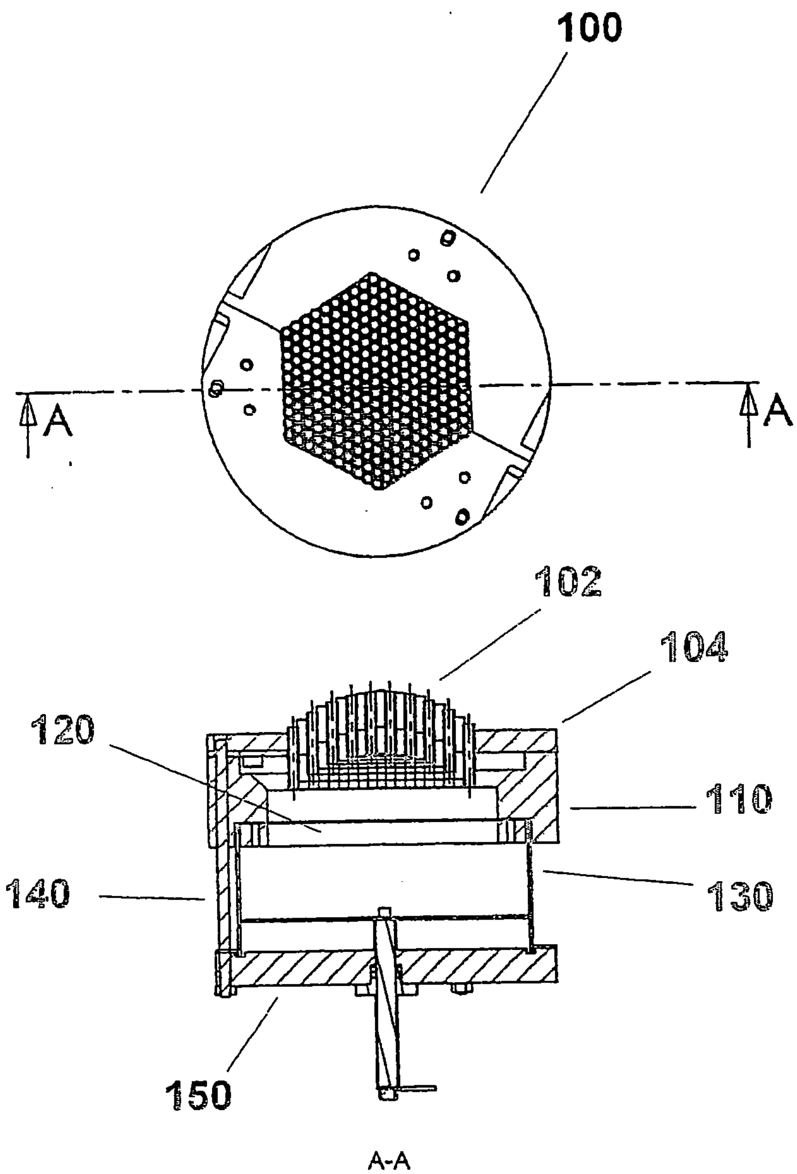

Figure 16

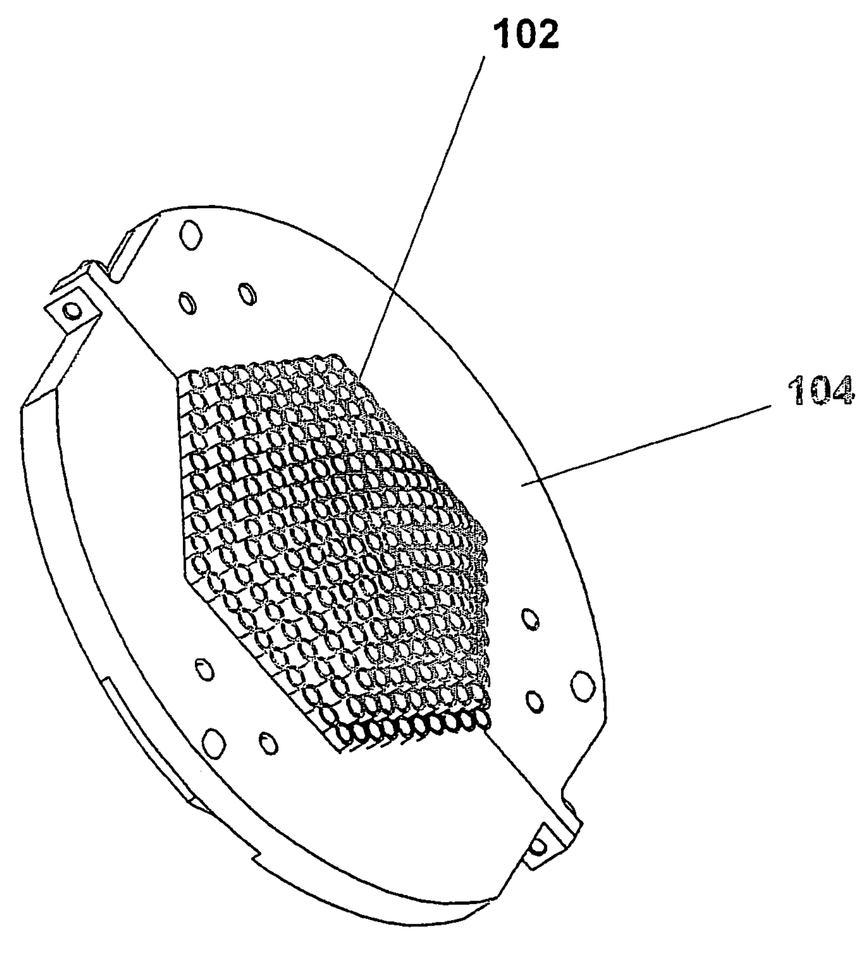

Figure 17

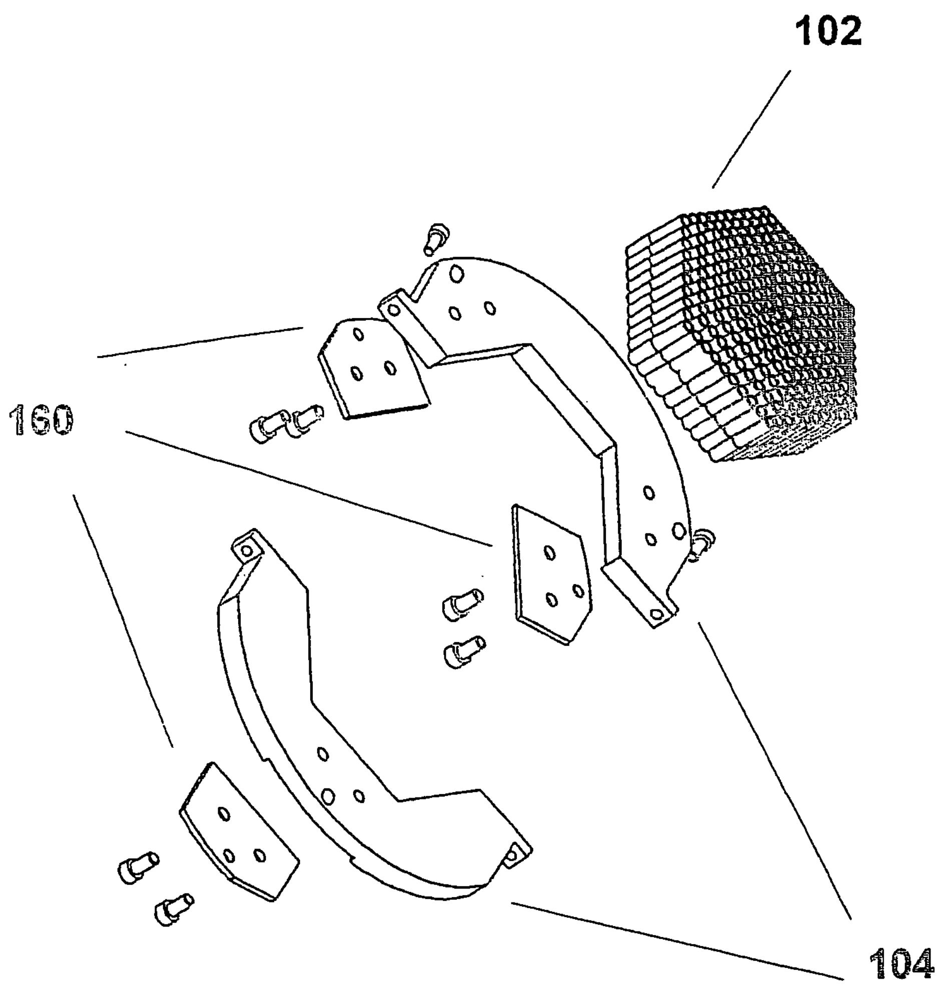

Figure 18

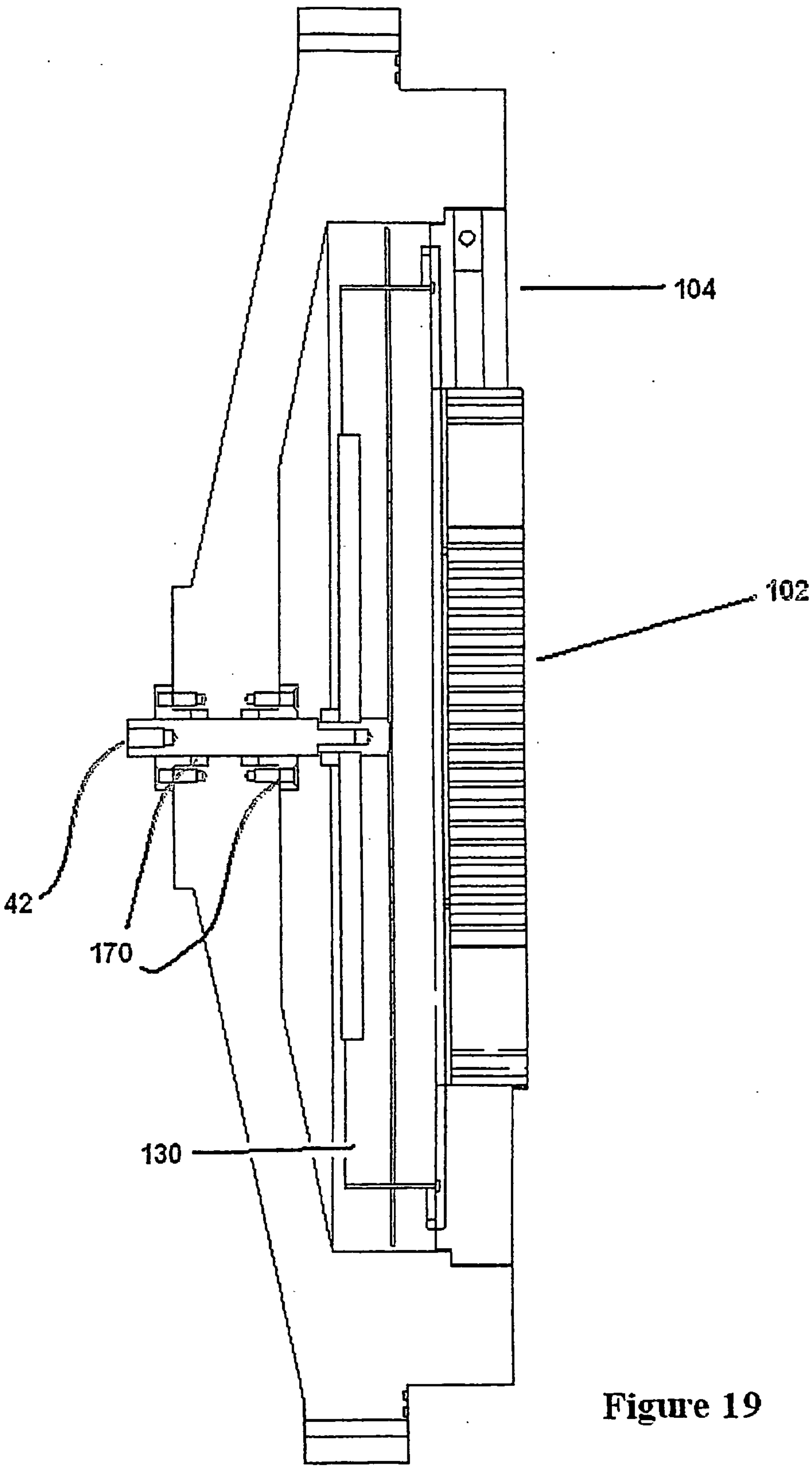

Figure 19

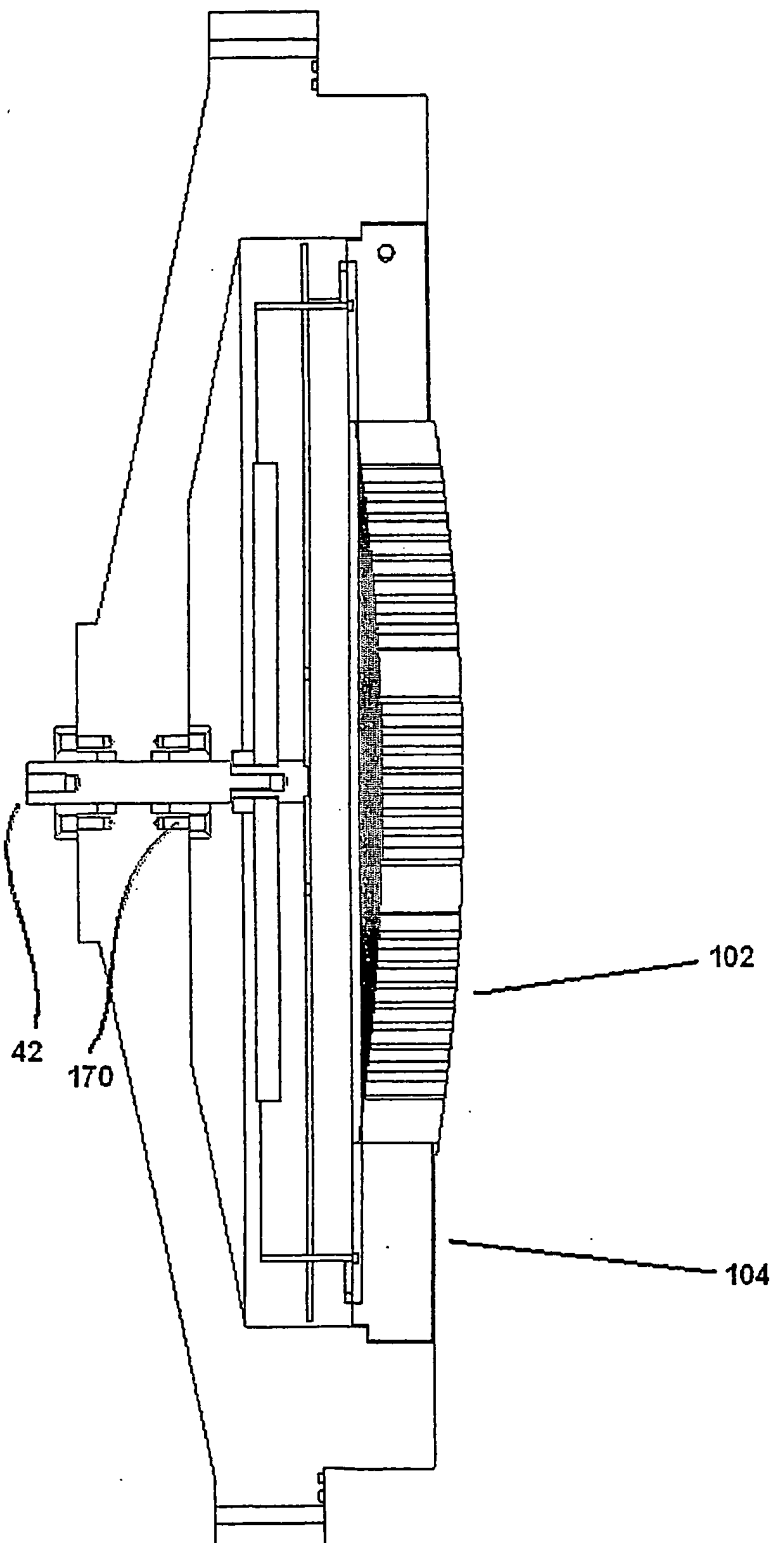

Figure 20

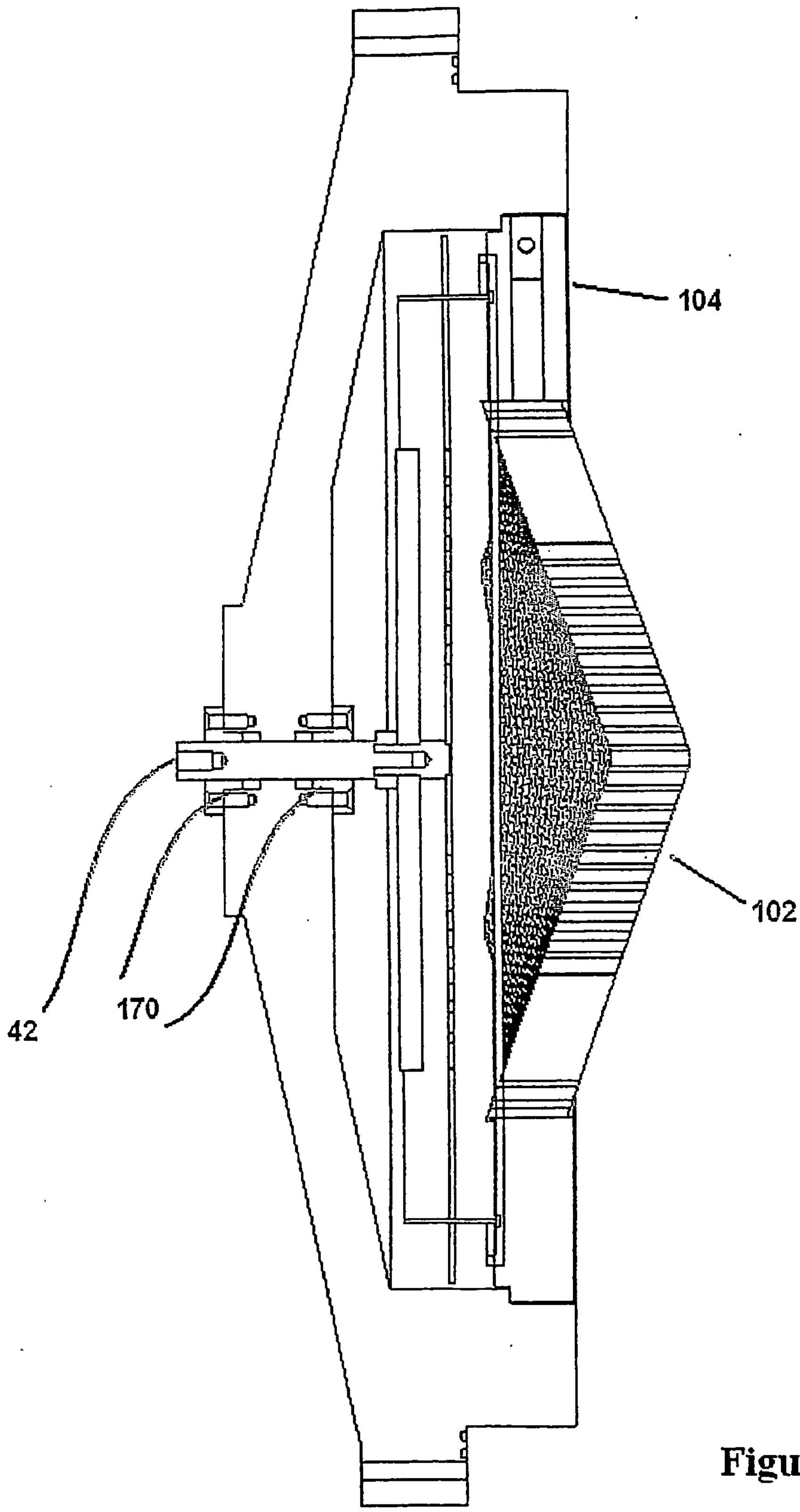

Figure 21

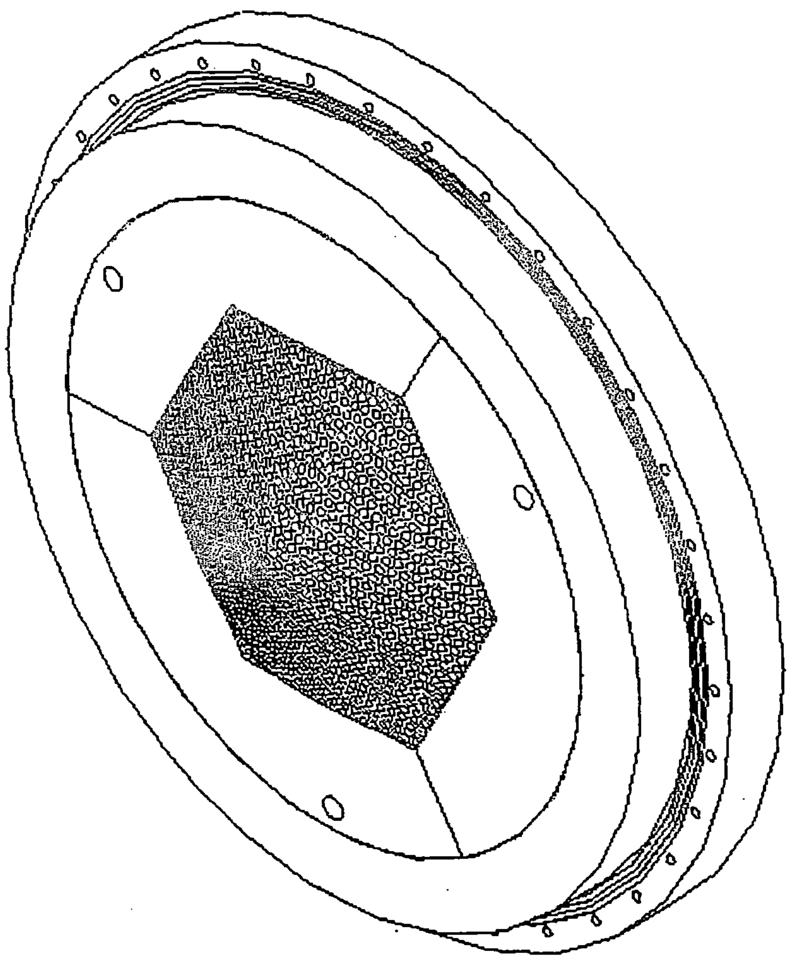

Figure 22

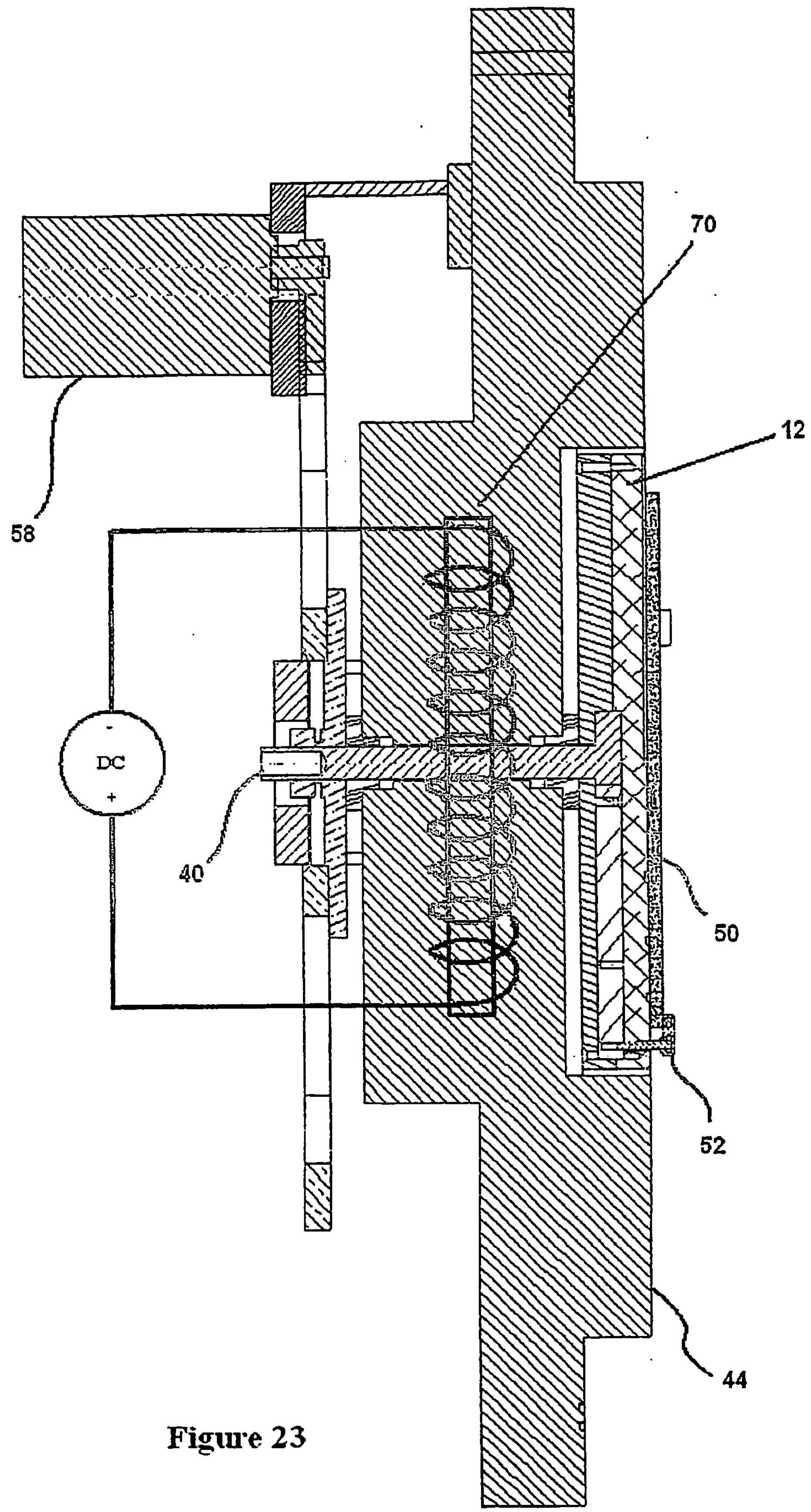

Figure 23

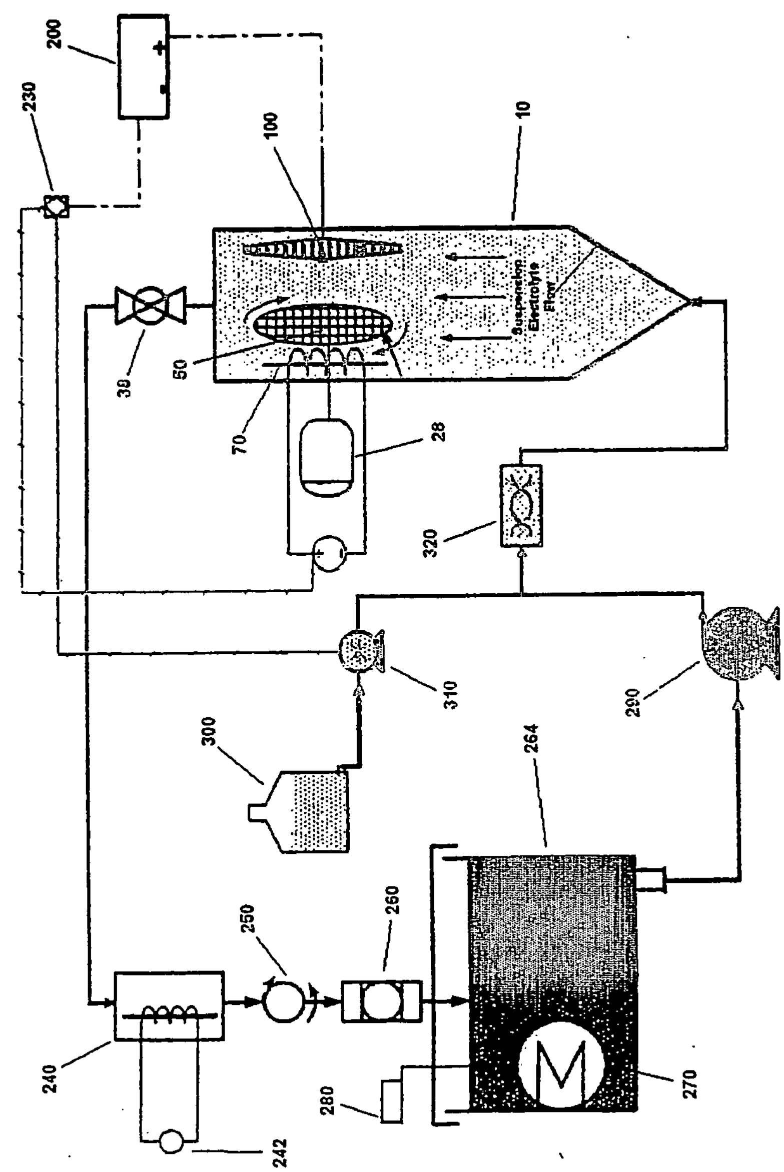
200
230
100
10
38
50
70
28
Suspension Electrolyte Flow
320
310
300
290
264
250
260
240
242
280
270
M

Figure 24

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US04/04277

A. CLASSIFICATION OF SUBJECT MATTER
IPC(7) : C25D 5/00, 17/00
US CL : 204/224R, 276, 275.1, 277; 205/88, 89, 90
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
U.S. : 204/224R, 276, 275.1, 277; 205/88, 89, 90

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
EAST: laminar near3 flow; electroplat$3

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
Please See Continuation Sheet

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 4,696,729 A (SANTINI) 29 September 1987 (29.09.1987), column 2-4	1-4, 6, 12, 16, 41
X	US 5,514,258 A (BRINKET et al) 07 May 1996 (07.05.1996), columns 3-6.	1, 6, 12-18, 22
A	US 4,278,245 A (DIBATTISTA et al) 14 July 1981 (14.07.1981)	
A	US 2,909,641 A (KUCYN) 20 October 1959 (20.10.1959)	
A	US 5,516,412 A (ANDRICACOS et al) 14 May 1996 (14.05.1996)	

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
02 August 2004 (02.08.2004)	02 SEP 2004
Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US Commissioner for Patents P.O. Box 1450 Alexandria, Virginia 22313-1450 Facsimile No. (703) 305-3230	Authorized officer Donald R. Valentine Telephone No. 571-272-1222